Infrared Stereo Calibration for Unmanned Ground Vehicle Navigation

Josh Harguess[a] and Shawn Strange[b]

[a]Space and Naval Warfare Systems Center Pacific, 53560 Hull St., San Diego, CA, USA
[b]Leidos, 10260 Campus Point Drive, San Diego, CA, USA

ABSTRACT

The problem of calibrating two color cameras as a stereo pair has been heavily researched and many off-the-shelf software packages, such as Robot Operating System and OpenCV, include calibration routines that work in most cases. However, the problem of calibrating two infrared (IR) cameras for the purposes of sensor fusion and point could generation is relatively new and many challenges exist. We present a comparison of color camera and IR camera stereo calibration using data from an unmanned ground vehicle. There are two main challenges in IR stereo calibration; the calibration board (material, design, etc.) and the accuracy of calibration pattern detection. We present our analysis of these challenges along with our IR stereo calibration methodology. Finally, we present our results both visually and analytically with computed reprojection errors.

Keywords: stereo calibration, infrared, IR, vehicle navigation

1. INTRODUCTION

The area of autonomous navigation for unmanned ground vehicles (UGV) is a rapidly growing field of research. There are many successful programs, such as the DARPA Grand Challenge[1] and the Google driverless car,[2] that are helping to drive this research into a reality. The US Navy, Department of Defense (DoD), and the Department of Homeland Security (DHS) are also becoming increasingly interested in unmanned vehicles for various applications.

Many challenges still persist in the area of autonomous (and even semi-autonomous) vehicle navigation for UGVs. One challenge is in detecting and classifying obstacles for avoidance and path planning. The use of laser-based sensors, such as Lidar, has become quite common for assisting in such a task, however, Lidar systems may be too expensive for certain application and are active, not passive, sensors, so they may not be desirable in some missions. Lidars are adversely effected by smoke, dust, fog, and rain. Therefore, the use of passive camera sensors, such as typical color and infrared (IR) cameras, has become an important research topic in UGV navigation. However, to build three-dimensional (3D) representations of the scene, a pair of stereo cameras (color, IR, or otherwise) must be accurately calibrated with respect to the rotation and translation between the two sensors. These are also known as the extrinsic parameters, and once known a disparity map may be computed from two synchronized images from the cameras. Once a disparity map is known, a depth image (3D points) may be computed.

One of the greatest challenges of using a stereo pair of color and/or IR cameras is to accurately determine the extrinsic calibration parameters between the pair of cameras. For color cameras, this has historically been solved using a checkerboard pattern of black and white squares using packages such as the Camera Calibration Toolbox for Matlab®,[3] OpenCV,[4] and the Robot Operating System (ROS).[5] However, the same packages do not necessarily work out-of-the-box for IR stereo cameras, due to thermal radiation required for high and low intensity pixels in an IR sensor. For instance, on a cold and cloudy day, there will be very little difference registered in an IR sensor between the black and white squares on a piece of paper. Therefore, more care and preparation is required in order to calibrate stereo IR cameras.

Please send correspondence to Josh Harguess:
E-mail: joshua.harguess@navy.mil, Telephone: 1 619 553 0777

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**

4. TITLE AND SUBTITLE **Infrared Stereo Calibration for Unmanned Ground Vehicle Navigation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Space and Naval Warfare Systems Center, Pacific, SPAWAR,53560 Hull St,San Diego,CA,92152-5001**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The problem of calibrating two color cameras as a stereo pair has been heavily researched and many o -the-shelf software packages, such as Robot Operating System and OpenCV, include calibration routines that work in most cases. However, the problem of calibrating two infrared (IR) cameras for the purposes of sensor fusion and point could generation is relatively new and many challenges exist. We present a comparison of color camera and IR camera stereo calibration using data from an unmanned ground vehicle. There are two main challenges in IR stereo calibration; the calibration board (material, design, etc.) and the accuracy of calibration pattern detection. We present our analysis of these challenges along with our IR stereo calibration methodology. Finally we present our results both visually and analytically with computed reprojection errors.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

This paper is organized in the following manner. First, we briefly introduce related works in the area of IR stereo camera calibration in Section 2. In Section 4, we discuss the two main challenges encountered in IR stereo calibration and our final methodology for IR stereo calibration. Finally, we present our results in Section 5 and conclude the paper in Section 6.

2. RELATED WORK

As previously noted, research into calibrating the extrinsic parameters for color stereo cameras is well established and vast. Existing calibration packages and libraries found in ROS and OpenCV have become standard approaches for computing extrinsic parameters in many practical applications. However, IR stereo calibration is a fairly new topic and is sparsely represented in literature.

One of the most extensive works on the subject is from Rankin et al.,[6] where the authors the details and applications of their perception system which relies on thermal and IR cameras (which they refer to as TIR). Their first TIR stereo calibration target consisted of a board with a pattern of symmetric circles with a light bulb placed behind each plastic circle insert. Another pattern simply consisted of pattern of symmetric circles, much like one of the patterns we use in our experiments. Their final calibration target used a checkerboard pattern background with a grid of fine wires around the boarders of the checker squares which, when current is applied, provides a very clear calibration target for both color and IR cameras. Ursine et al.[7] introduce a methodology for reliably calibrating color and IR stereo cameras using a checker calibration board with a copper plate background (with low emissivity) and black squares painted on with a high emissivity spray ink. This way, both the color and IR cameras may view the pattern and attain a similar differential between the boundaries of the squares for pattern detection. Another example IR stereo system, developed by Kong et al.,[8] is a system for autonomous landing of an unmanned aerial vehicle using a ground-based IR stereo system. Their methodology for calibrating the extrinsic parameters for the IR cameras was to paste black squares on a mirror and then actively heat the mirror to achieve the classic checker board pattern commonly used in calibration. The accuracy of their calibration was not discussed in the paper. In the work of Starr and Lattimer,[9] a pair of IR cameras are used to compare visibility in fire conditions between IR stereo and Lidar sensor systems. They calibrate the cameras using a pattern that is formed from a cold metal grid being placed in front of a black body radiation source (liquid-crystal display computer monitor). Another application of IR stereo cameras is found in the work of Bertozzi, Broggi, and Lasagni.[10] In their work, the extrinsic parameters between two IR cameras are used to triangulate the position and distance of detected objects in a scene which further assists in refining their methodology for pedestrian detection from their IR camera system. While their results look promising, their methodology for calibrating the two IR stereo cameras is not discussed in the paper.

In our work, we had limited resources available for heating, illuminating and otherwise building a calibration board from new materials from scratch. Instead, we present an analysis using three black and white calibration patterns; checkerboard, symmetric circles, and asymmetric circles.

3. SYSTEM DESCRIPTION

Our UGV is based on the TORC ByWire XGV™, shown in Figure 1(a). For IR imagery, we use two FLIR® Tau® 640 35mm cameras with a baseline of approximately 0.5m. For color imagery, we use two Prosilica GC750 cameras from Allied Vision Technologies with a baseline of approximately 1m. There are several challenges inherent to such a system, such as the wide baselines and outdoor weather conditions, that will be addressed in this paper. Synchronization of the cameras is assumed for the content of this work.

4. CHALLENGES AND METHODOLOGY

There are numerous challenges present when attempting to calibrate a stereo pair of IR cameras. In this paper, we will cover the two most difficult challenges found in our experience; the calibration board (material, design, etc.) and the accuracy of calibration pattern detection.

(a)

(b)

Figure 1. TORC ByWire XGV (a) and camera sensors (b)

4.1 Calibration Board

The first challenge, that has been mentioned by several authors previously, is the calibration board itself. Unlike the calibration pattern for color stereo cameras, which can utilize simple black and white checkerboard patterns for highly accurate calibration, the calibration pattern for two IR stereo cameras must be carefully selected, designed, and/or manufactured. Rankin et al.[6] use small light bulbs behind a circular pattern and a grid of wires placed on a checkerboard pattern. Ursine et al.[7] use a checkerboard pattern painted on a copper plate background. Kong et al.[8] use a heated mirror with black squares painted on for a checkerboard pattern. And finally Starr and Lattimer[9] use a cold metal grid heated by a computer monitor. Related to the above challenges are the wide baseline between the two cameras, which requires larger calibration boards than standard boards, and the many challenges faced with calibrating in an outdoor environment, such as uncontrolled lighting, wind, dust, and other difficult to predict weather conditions. While we did not have the resources to build the patterns described by the authors above, we were able find a solution to these challenges, which we will describe below.

4.2 Calibration Pattern

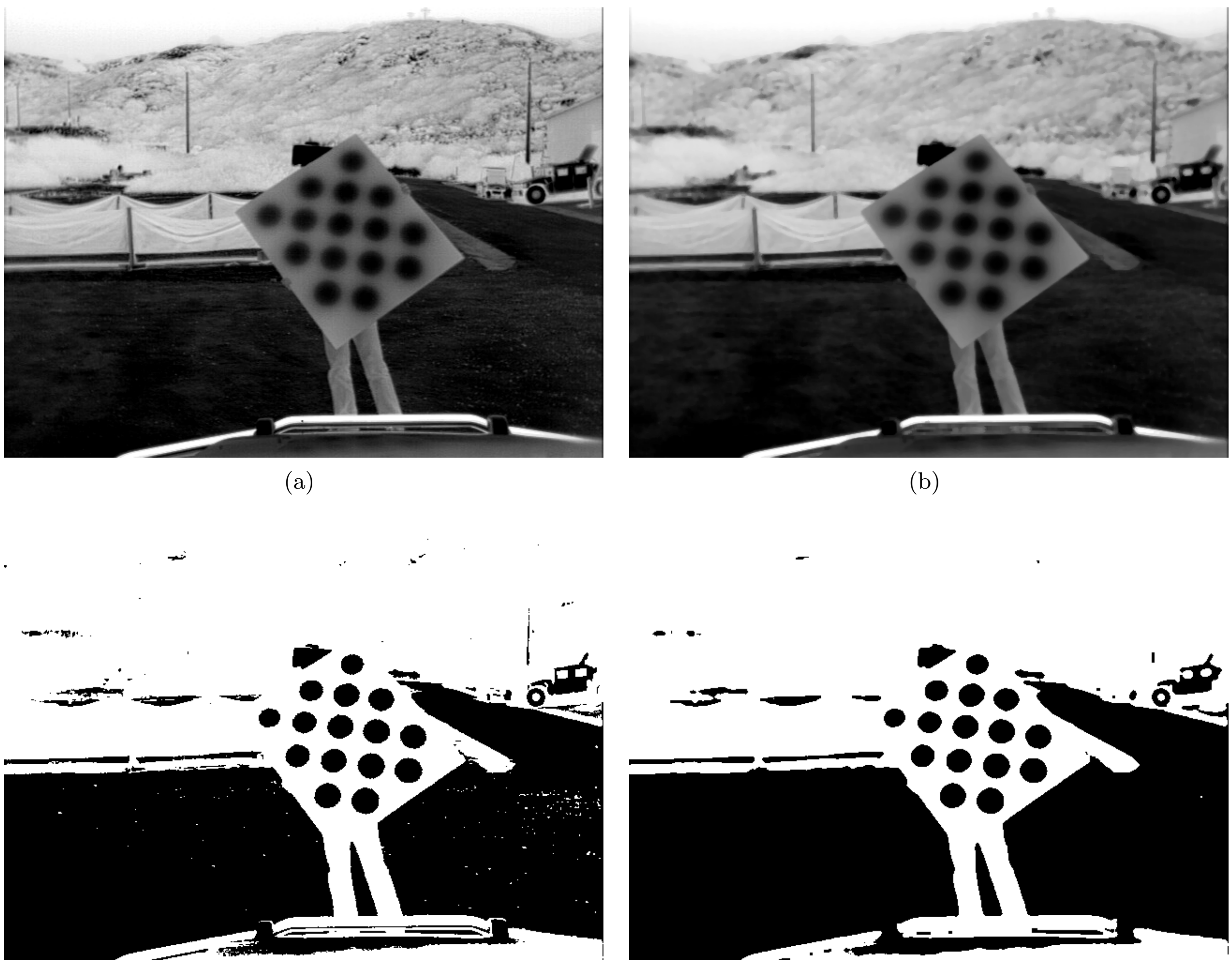
The second challenge we encountered was the calibration pattern itself. We started with the classic black and white checkerboard pattern, but the dynamic range between the "white" and "black" squares was not sufficient for the calibration routine to detect the pattern. Even when we increased the size of the calibration board from 10cm squares to 15cm squares, the detection algorithm was unsuccessful. An example of this challenge in dynamic range is shown in Figure 6. Next we tried a pattern of symmetric circles, but since each circle was only 5.08cm in diameter, they were difficult to detect at the distances needed for the baseline between the two cameras. Heating was tried (both with a portable heating device and direct sunlight) on both the checkerboard pattern and the symmetric circles pattern, but the calibration routine still failed to detect the patterns successfully. In addition to the trouble with our available calibration patterns, the software we used to compute the calibration suffered from setbacks as well. For instance, the "Fuerte" version of ROS we used did not support circle patterns for calibration, so we used OpenCV to compute the calibration parameters offline.

4.3 Final Methodology

Our final methodology that was successful in calibrating our IR stereo cameras was the following. First, we used a calibration board manufactured by 858 Graphics, Inc. that was made from dibond, which is a lightweight, rigid and durable aluminum composite material. The board was ordered to be $\frac{1}{8}in$ white dibond with no laminate. 858 Graphics, Inc. recently switched to a new manufacturing process where they print the patterns directly onto the dibond and this resulted in a much improved ability to detect the patterns with IR cameras. The pattern printed onto the boards was a 3 by 5 pattern of asymmetric circles with a 17cm diameter with a spacing of 17cm between the circles. Also, we found that by using this large asymmetric circles pattern on a warm day with little

to no wind (with the board left in direct sunlight), the results detection results improved dramatically. Example data taken from two IR cameras of the final calibration board in good conditions is found in Figure 7.

Additionally, simple preprocessing techniques were used to try to increase the accuracy of IR stereo calibration. Three methods were used and are briefly described. In the first method, we applied a median blur filter to each IR image with a window of 5 pixels. For the second method, we used a thresholding function to truncate the pixel values above an intensity of 50. The third method simply combines the first two methods. Example images of the median blur filter, thresholding, and the combination of the two are shown in Figures 2(b), 2(c), and 2(d), respectively.



(a) (b) (c) (d)

Figure 2. Example images of IR image preprocessing; (a) original image, (b) median blurred image, (c) thresholded image, and (d) combined

5. RESULTS

For our experiments with the color cameras in our system, checkerboard patterns, symmetric circle patterns and asymmetric circle patterns where all successfully used in our calibration routine. Example images of each of these patterns is shown in Figures 3, 4, and 5, respectively. For our experiments with the IR stereo cameras, only the asymmetric circle patterns were successfully used in calibrating the cameras. Examples of these images are found in Figure 7. An example of a failure mode with the checkerboard pattern in the left IR camera is shown in Figure 6.

To evaluate the stereo calibration results numerically, we used OpenCV to calculate the stereo reprojection error for each of the calibration patterns used for both the color stereo cameras and the IR stereo cameras. The OpeCV function "stereoCalibrate" returns the RMS reprojection error which is computed by transforming the 3D points of the calibration board using the computed extrinsic parameters to both the left and right image and comparing those projected points to the detected corners or circle centroids.

The results are shown in Tables 1 and 2.

Calibration pattern	Image pairs detected / total images	Dim (wxh)	Pattern size (cm)	RMS reprojection error
Checkerboard	38/38	6x5	15	0.810
Small circles	42/42	10x9	5.08	0.458
Asymmetric circles	53/60	3x5	17	0.348

Table 1. Stereo reprojection error of color stereo cameras

Calibration pattern	Image pairs detected / total images	Dim (wxh)	Pattern size (cm)	RMS reprojection error
Checkerboard	0/38	6x5	15	N/A
Small circles	0/42	10x9	5.08	N/A
Asymmetric circles	40/129	3x5	17	3.683
Asymmetric circles (median blur)	21/129	3x5	17	0.743
Asymmetric circles (threshold)	40/129	3x5	17	0.501
Asymmetric circles (median blur+threshold)	68/129	3x5	17	0.239

Table 2. Stereo reprojection error of IR stereo cameras

In Table 2, the reprojection errors were "N/A" for the calibration patterns which were not detected by the calibration routine. However, the asymmetric circle patterns were successfully detected with and without image preprocessing. Clearly, the simple preprocessing done to the IR imagery improved the IR stereo calibration results. As shown in Table 1, even the color stereo cameras benefit in reprojection error when using the asymmetric board for stereo calibration.

6. CONCLUSION AND FUTURE WORK

We have presented our analysis and methodology for calibrating a pair of IR stereo cameras. The two most difficult challenges faced in this work were the calibration board and the calibration pattern. Our final methodology uses an asymmetric calibration pattern printed on a dibond board. When left in direct sunlight before calibration, the board is used to successfully calibrate our IR stereo cameras with no image preprocessing resulting in acceptable stereo reprojection error. For future work, we have plans to integrate our OpenCV calibration routine into ROS and implement further preprocessing techniques for the IR imagery, such as adaptive thresholding and background subtraction. Additionally, we plan on exploring the next steps of feature matching for creating disparity maps which will lead to the generation of point clouds from our IR stereo cameras. We also plan on exploring other easy-to-manufacture materials for calibration of both color and IR stereo cameras. Additionally, we would like to explore other calibration patterns which might be beneficial.[11]

REFERENCES

[1] Thrun, S., Montemerlo, M., Dahlkamp, H., Stavens, D., Aron, A., Diebel, J., Fong, P., Gale, J., Halpenny, M., Hoffmann, G., et al., "Stanley: The robot that won the darpa grand challenge," *Journal of field Robotics* **23**(9), 661–692 (2006).

[2] Thrun, S., "Toward robotic cars," *Communications of the ACM* **53**(4), 99–106 (2010).

[3] Bouguet, J.-Y., "Camera calibration toolbox for matlab," (2004).

[4] Bradski, G. and Kaehler, A., [*Learning OpenCV: Computer vision with the OpenCV library*], O'Reilly Media, Inc. (2008).

[5] Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., Wheeler, R., and Ng, A. Y., "Ros: an open-source robot operating system," in [*ICRA workshop on open source software*], **3**(3.2) (2009).

[6] Rankin, A., Huertas, A., Matthies, L., Bajracharya, M., Assad, C., Brennan, S., Bellutta, P., and Sherwin, G. W., "Unmanned ground vehicle perception using thermal infrared cameras," in [*SPIE Defense, Security, and Sensing*], 804503–804503, International Society for Optics and Photonics (2011).

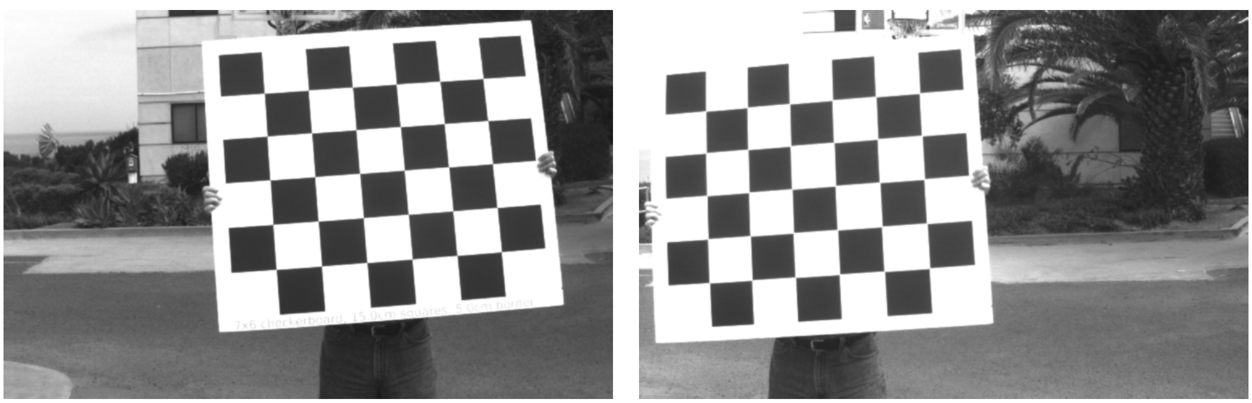
[7] Ursine, W., Calado, F., Teixeira, G., Diniz, H., Silvino, S., and de Andrade, R., "Thermal/visible autonomous stereo visio system calibration methodology for non-controlled environments," in [*11th International Conference on Quantitative Infrared Thermography*], (2012).

[8] Kong, W., Zhang, D., Wang, X., Xian, Z., and Zhang, J., "Autonomous landing of an uav with a ground-based actuated infrared stereo vision system," in [*Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*], 2963–2970, IEEE (2013).

[9] Starr, J. W. and Lattimer, B., "A comparison of ir stereo vision and lidar for use in fire environments," in [*2012 IEEE sensors 2012 conference*], (2012).

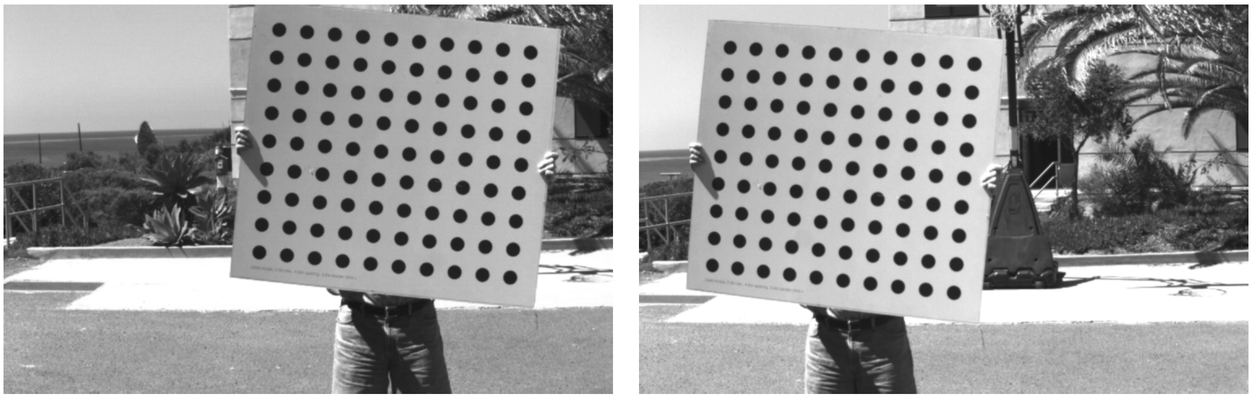
[10] Bertozzi, M., Broggi, A., Lasagni, A., and Rose, M., "Infrared stereo vision-based pedestrian detection," in [*Intelligent Vehicles Symposium, 2005. Proceedings. IEEE*], 24–29, IEEE (2005).

[11] Oyamada, Y., Fallavollita, P., and Navab, N., "Single camera calibration using partially visible calibration objects based on random dots marker tracking algorithm," in [*The IEEE and ACM International Symposium on Mixed and Augmented Reality, Workshop on Tracking Methods and Applications (TMA), Atlanta, USA*], (2012).



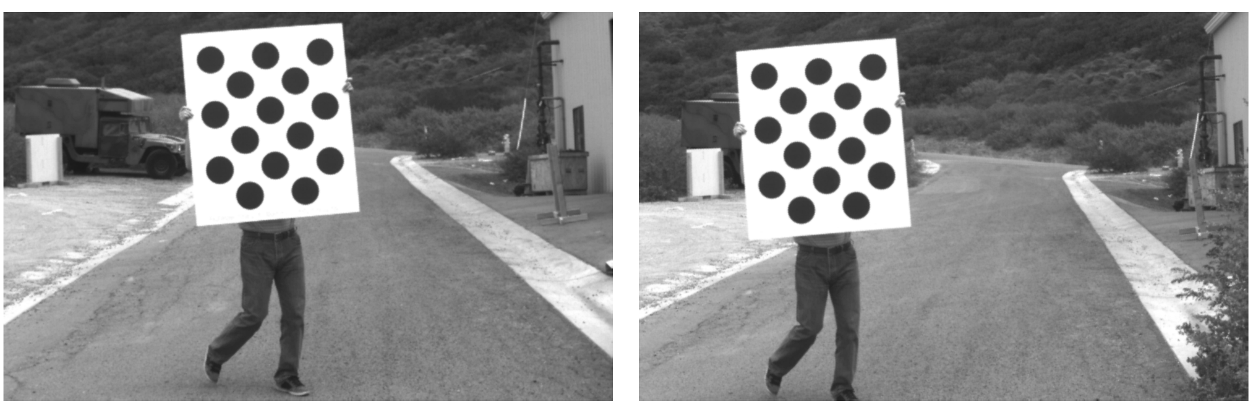
(a) (b)

Figure 3. Checker board pattern for left (a) and right (b) color cameras



(a) (b)

Figure 4. Symmetric circle board pattern for left (a) and right (b) color cameras



(a) (b)

Figure 5. Asymmetric circle board pattern for left (a) and right (b) color cameras

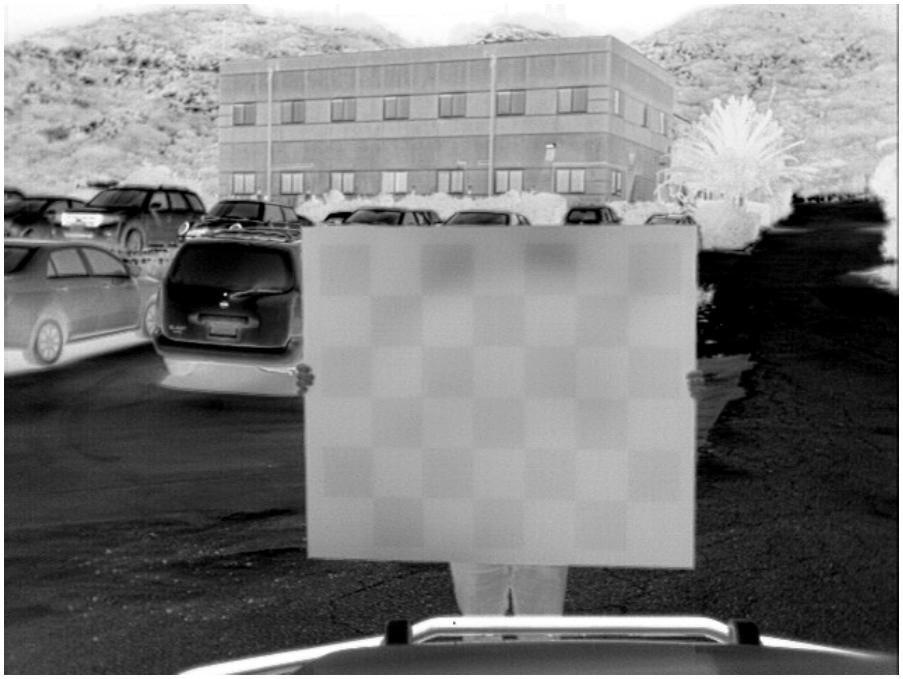


Figure 6. Example image of the checker board pattern from left IR camera

(a)

(b)

Figure 7. Asymmetric circle board pattern for left (a) and right (b) IR stereo cameras